REVIEW

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Feeding efficiency of sheep as a strategy for mitigating greenhouse gas emissions

Eficiência alimentar de ovinos como estratégia para mitigação de gases de efeito estufa

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ABSTRACT: Climate change is a very relevant and worrying topic today and is present in the agendas of different spheres of society. High concentrations of greenhouse gases (GHGs) are released into the atmosphere, causing global temperatures to rise. In agricultural production, methane (CH_4) is considered one of the highest GHG emissions, causing a negative impact on natural resources and accelerating climate change. In the coming years, with the increase in the world population, food production should be implemented in self-sufficient, quality, and sustainable production systems to meet the need for high consumption. The reduction in CH_4 production is related to the better efficiency of energy use of the feed by the animals; therefore, the knowledge of the ruminal fermentation parameters, identification of the ruminal microbiota, and selection of more efficient animals, with lower consumption and greater weight gain, in addition to producing less GHGs like CH_4, have a less negative impact on the environment and are economically viable. This review presents some aspects of selection for feed efficiency in sheep as a strategy to mitigate GHG emission and some techniques for measuring these gases.

KEYWORDS: CH_4; feed efficiency measures; ruminal fermentation parameters; sustainability.

RESUMO: As alterações climáticas são tema muito relevante e preocupante na atualidade e está presente nas pautas de diferentes esferas da sociedade. Altas concentrações de gases de efeito estufa são lançados na atmosfera, fazendo com que a temperatura global se eleve. Na produção agrícola, o metano (CH4) é considerado uma das maiores emissões de GEE, causando impacto negativo nos recursos naturais e acelerando as mudanças climáticas. Nos próximos anos, com o aumento da população mundial, a produção de alimentos deverá estar implementada em sistemas produtivos autossuficientes, de qualidade e sustentáveis para suprir a necessidade do elevado consumo. A redução na produção de CH4 está relacionada com a melhor eficiência do uso de energia da ração pelos animais; portanto, o conhecimento dos parâmetros da fermentação ruminal, identificação da microbiota ruminal e seleção de animais mais eficientes, com menor consumo e maior ganho de peso, além de produzirem menos GEEs como o CH4, impactam menos o meio ambiente e são economicamente viável. Esta revisão apresenta alguns aspectos da seleção para eficiência alimentar em ovinos como estratégia para mitigar a emissão de GEE e algumas técnicas para mensuração desses gases.

PALAVRAS-CHAVE: CH_4; medidas de eficiência alimentar; parâmetros fermentativos ruminais; sustentabilidade.

INTRODUCTION

With the increasing human population, the demand for food of animal origin, and therefore the need to use natural resources, will considerably increase, which can consequently impact the availability of natural resources in the environment. It is estimated that, by 2050, the world population will reach 9.7 billion; thus, it is necessary to increase agricultural production, as well as improve the distribution of agricultural products and reduce the wastage of food produced (FAO, 2017). Currently, climate change is one of the main subjects discussed worldwide; at the last Climate Change Conference (COP26), the main discussion was related to the commitment that the countries agreed to in terms of reducing environmental impacts. These commitments included the end

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of deforestation; fight against climate change; destruction of biodiversity and hunger; provision of biosecurity; and protection of the rights of peoples and societies most affected by climate change (UN News, 2021).

The livestock sector makes a relevant contribution to climate change, mainly through the emission of greenhouse gases (GHGs) from ruminant production. Ruminants emit methane (CH_4) as part of the natural process of enteric fermentation, preventing the accumulation of hydrogen (H_2) in the rumen. In addition to representing energy loss for animals, CH_4 is a GHG with a global warming potential greater than that of carbon dioxide (CO_2) and is one of the biggest causes of global warming. Despite being criticized for producing considerable CH_4, ruminant livestock activity has a competitive advantage of transforming products of low nutritional value for humans into useful products.

In this livestock scenario, beef sheep farming can be a beneficial production, export, and profit activity and have a much more sustainable production cycle, since it is shorter, in relation to, for example, cattle farming. Sheep are quite adaptable to different habitats and, during the cycle, can emit fewer GHGs, especially CH_4.

Raising animals in intensified systems in confinement is a practice that can enable their faster productive exploitation; however, there must be more financial control, as it can become economically unfeasible, especially in relation to the high costs of food. Thus, animal selection that use the nutrients in the diet more efficiently—in addition to reducing production costs, generating less pollutants (both GHGs and waste), and using fewer inputs—yields more sustainable production.

Challenges and sustainable potential of sheep production

The sustainability of animal production depends on economic, environmental, and social factors, in addition to efficient management (RUIZ MORALES; CASTEL GENÍS; GUERRERO, 2019). The production of small ruminants plays a significant socioeconomic and environmental role in society. Traditionally, these animals are raised in systems where the land is less productive or poor compared to the land used for raising cattle, for example. Raising small ruminants requires lower initial investments, in addition to yielding good economic results, due to their shorter production cycle (SEJIAN et al., 2021). Sheep farming has emerged as a livelihood practiced in many regions globally. Due to its high adaptability to different climates, it is a source of food and income for many families. It has aroused interest because it is considered an alternative activity for diversifying agricultural production, which can guarantee profits. The trends in the sheep market are promising, since the increase in the world population will significantly impact food production. The demand for food of animal origin in developing countries has been driven by this demographic growth, urbanization, and the variations and preferences of dietary habits (FAO, 2017).

Recently, the consumer market has been increasingly concerned with the food they consume, not only with regard to the quality of the product itself but also with issues of safety and the environmental impact of its production (ANDRADE et al., 2020; BARBOSA et al., 2022). The current transformations of the world market, mainly due to climate change and the COVID-19 pandemic, constitute both challenges and opportunities for structuring the food production chain and the sheep industry. Attention to health standards and good production and manufacturing practices on a large scale are reflections of the sophistication and intensification of the consumer market that values quality and food safety. The production chain needs to adapt, especially with regard to sustainable production, respecting natural resources, with relatively low impact on the environment and climate, creating more efficient production conditions by using safe and quality technologies (FAO, 2021).

GHG production and its relationship with animal production

Climate change is a highly relevant topic today in decision-making in politics, economy, society, environmental issues, and science, with its presence on the agendas of different spheres of society. The scientific class points to anthropogenic action as a major cause of global warming, relating it to an increase in GHG emissions. This relationship is often denied or questioned, causing interference in information and understanding (LEITE, 2014).

From 1890 onwards, through the research by the Swedish scientist Savante Arrhenius on the influence of CO_2 on the greenhouse effect, the topic of global warming has gained popularity and importance, especially since the 2000s (FLEURY; MIGUEL; TADDEI, 2019). The greenhouse effect is a real phenomenon that is well understood in science. There is a natural and beneficial greenhouse effect that keeps planet Earth warm and is essential for the survival of species. However, there is also the greenhouse effect caused by the excessive increase in the production and emission of GHGs in the atmosphere, mainly due to anthropogenic activities. GHGs allow solar radiation to enter the atmosphere but make it difficult to leave, causing heat accumulation (TILIO NETO, 2010). Global warming, the greenhouse effect, and climate change are interrelated. When high concentrations of GHGs are released into the atmosphere, the global temperature rises, causing global warming and, consequently, climate change.

The main GHGs are CO_2, CH_4, and nitrous oxide (N_2O). These three gases are derived from both natural and anthropogenic sources, and human action plays an important role in increasing their concentrations in the atmosphere. Of the three, CO_2 has the highest potential to generate the greenhouse effect as it is released into the atmosphere in more significant quantities and its radiative forcing takes centuries to begin to decrease. The radiative forcing of a gas is its ability to cause climate change (IPCC, 2017). The second gas that contributes the most to the greenhouse effect is CH_4, with its radiative forcing 21 times greater than that of CO_2 (TILIO NETO, 2010).

CH_4 is a potent greenhouse gas capable of trapping 21 times more heat than CO_2. Its lifetime in the atmosphere is 9–15 years, and in the last two centuries, its atmospheric concentration has more than doubled compared to CO_2. In Brazil and in developing countries, the emissions from the agricultural sector in general are projected to continue to increase, mainly due to advances in world population growth.

The consequences of climate change involve fundamental questions about human existence. Extremely high temperatures; drop in food production; decrease in fresh water supply; species extinction; highly volatile climate with storms, rains, and tornadoes; deforestation and desertification; damage to poles and glaciers; transformation of sea currents; and economic impact with fall in the world GDP, which profoundly affect the poorest populations (TILIO NETO, 2010; LANE, 2018).

Facing climate challenges is a task that involves responses at various levels, being social, local, national, regional, or in the broader global sense. The frequently held meetings and world conferences aim to seek solutions among countries in terms of reducing global warming and GHG emissions. Scientific research supports the hypothesis that the climate system has been undergoing changes caused by global warming. Considerable recent and more secure evidence has emerged regarding this correlation. This evidence appears in increases in global average temperature, and the Earth's temperature has indeed been found to increase (IPCC, 2018).

Some alternatives should be further studied to solve the problem of global warming. Of these, the use of renewable energy is a main pillar, since much of our energy comes from non-renewable sources. Any change involves large investments and financing, which in many cases would be difficult in underdeveloped countries. Innovations need to be made in every way possible— improving the use of natural resources, which can create balance at social, cultural, and economic development levels; engaging a set of sustainable global policies to be implemented and managed particularly in terms of forecasting the increase in world population, which will drastically affect the demand for resources and food (LANE, 2018); and taking actions capable of being carried out and attainable, which will benefit everyone. Therefore, it is up to the scientific community to continue working toward its advancement and investigating ways of adapting to these climate changes since they are already part of our reality.

The production of food of animal origin is extremely important for the world's supply. The livestock sector stands out for its economic, social, and political relevance. A large share of global GDP is related to this sector, generating billions of jobs and providing livelihood to thousands of families (FAO, 2009). On similar lines, in the Brazilian context, livestock stands out as being one of the most profitable activities in agribusiness. The exploitation of animal production, given its relevant importance, must be self-sufficient and sustainable (LENG, 2005; PRIMAVESI, 2007). However, there is a great impact on natural resources and a high contribution to climate change (FAO, 2009).

GHG emissions from the agricultural sector account for approximately 22% of the planet's total emissions. Of these, 44% are in the form of CH_4, 29% in N_2O, and 27% in CO_2 (FAO, 2013). In the agriculture sector, the main sources of direct emission are the cattle herd, which emit considerable CH_4 through ruminal enteric fermentation, followed by animal waste management, cultivation of irrigated rice, and burning of residues, such as sugarcane straws (Lobato; Rodrigues; Santos, 2019). Cattle, within the agro sector, are the main contributors to GHG emissions, with approximately 4.6 Gt of CO_2-eq, representing 65% of the sector's emissions. Small ruminants have much lower emission levels (6.5%), totaling 475 Mt of CO_2-eq, of which 299 million tons come from meat production, with an average emission intensity of approximately 23.8 kg of CO_2-eq/kg of meat produced (FAO, 2013).

In some countries, CH_4 and N_2O emissions from animal production processes generate financial penalties related to the imposition of limitations on carbon emissions by environmental legislation (MOSS; JOUANY; NEWBOLD, 2000). In addition to environmental impacts, the elimination of CH_4 represents an energy loss of approximately 5–10% of the total energy consumed by animals (MADSEN et al., 2010; COTA et al., 2014).

Much of the enteric production of CH_4 occurs in the reticulum–rumen (MURRAY; BRYANT; LENG, 1976). The rumen has a large and diverse population of highly specialized anaerobic prokaryotic microorganisms that live in a symbiotic and mutualistic process, encompassing bacteria, fungi, and protozoa (MACKIE, 2002; NEWBOLD, 2005). CH_4 is formed through the reduction of CO_2 from ingested food; four molecules of H_2 with one molecule of CO_2 produce CH_4 (STEVENS and HUME, 1998). This reduction is carried out by microorganisms called Archeas, which represent 0.5–3.0% of the microbial community in the digestive tract (HACKMANN; SPAIM, 2010). This hydrogen plays a key role in maintaining rumen health and must be removed to maintain efficient fermentation, correct forage degradation, provide an environment conducive to microbial growth, and produce short-chain fatty acids (SCFAs).

In the rumen, through the diverse flora present, there is also SCFA formation. SCFAs are absorbed and used as an energy source, while most of the CO_2 and CH_4 are eliminated from the rumen through eructation. Alcohols and lactate are also formed during these processes; however, it has recently been recognized that they are relatively less important in the rumen (except in cases where lactate accumulates in the rumen and causes acidosis) (HRISTOV et al., 2013). As noted by Van Soest (1994), the basis of the problem of anaerobic metabolism is the storage of oxygen in the form of CO_2 and the release of hydrogen ions in the form of CH_4.

If the reduction in CH_4 production is related to a more efficient use of energy from food by animals, it is interesting to seek strategies to mitigate CH_4 emission in association with better productive performance (SHIBATA; TERADA, 2010).

CH_4 emission measurement techniques and mitigation strategies

To measure and quantify CH_4 production, different techniques have been developed. The application of each technique depends on the production system to be evaluated, adapting to the reality of each system and always maintaining maximum accuracy in measurements (MORGAVI et al., 2010; MACHADO et al., 2011; HAMMOND et al., 2016).

In the measurement of emission *in vivo*, we can highlight the use of CH_4 laser detectors or automatic individual measurement systems, such as GreenFeed (C-Lock Inc., Rapid City, South Dakota, USA); respirometric chambers (ABDALLA et al., 2012); and sulfur hexafluoride (SF_6) tracer gas technique (JOHNSON et al., 1994; NEW ZEALAND, 2014; RICCI et al., 2014; HAMMOND et al., 2016; LIMA et al., 2020).

Respirometric chambers have been used for over 100 years (ARMSBY, 1903; HAMMOND et al., 2016). There are various respirometric chambers, ranging from metabolic cages covered with polyethylene plates to more expensive modern calorimetry systems (ABDALLA et al., 2008; NEW ZEALAND, 2014). The respirometric chambers work as follows: the external air enters the chamber, circulates through it, and mixes with the gases emitted by the animal. By comparison and from the difference between the gases present inside the chamber, the concentrations of these gases CO2, N2O and CH_4 can be determined (LIMA et al., 2019). The parameters of ambient humidity and air flow velocity in the chamber are also considered, and the data are corrected for normal conditions of temperature and pressure (HAMMOND et al., 2016). Tests in respirometric chambers are usually conducted for 24-h periods, ranging from 1 to 7 consecutive days (VAN ZIJDERVELD et al., 2010; EL-ZAIAT et al., 2014; SCHWARM et al., 2015).

Enteric CH_4 emissions are proportional to the dry matter ingested; therefore, these emissions are commonly expressed on the basis of dry matter consumption as, for example, CH_4/Kg of ingested dry matter consumption or as a percentage of the ingested gross energy. For sheep, the daily CH_4 emission is approximately 22–25 g/day (COTTLE; NOLAN; WIEDEMANN, 2011).

There are many techniques that can be used to mitigate CH_4 emission by ruminants, most of which are related to animal feeding. The production of CH_4 can vary with the diet, composition, and quality of the same, dry matter intake, as well as for grazing animals: grazing period and forage quality (ARCHIMEDE et al., 2011; SOREN; SEJIAN; MALIK, 2015; HRISTOV et al., 2018). Improving animals' diet, providing better-quality pastures, using adequate supplementation, and selecting the most efficient animals can be advantageous in addition to increasing the production capacity, as well as reducing the expenses and cycle length and expenses, especially with feeding, as in the reduction of CH_4 emissions (COTTLE; NOLAN; WIEDEMANN, 2011; BERCHIELLI et al., 2012).

The ruminal microbiota plays an important role in CH_4 production (ECKARD; GRAINGER; DE KLEIN, 2010), and the diet is related to the construction of existing microbiota in the rumen, which can influence the number and proportion of different species present, impacting their metabolic activity (ARCURI et al., 2006). Although many species are present in the rumen at all times, the growth rate of each species, as well as the digestive action, may vary with ruminal conditions. Methanogenic Archaea are the most sensitive to changes in the rumen environment. As they are the main users of hydrogen, the balance of their population affects rumen metabolism, carbon balance, and, consequently, CH_4 production (ARCURI et al., 2006). According to Machado et al. (2011), with an increase in the concentrate proportion in the diet, CH_4 emission can be reduced as a proportion of ingested energy or expressed per unit of animal product (meat/milk/wool). The replacement of fibrous carbohydrates (cellulose and hemicellulose) by nonfibrous carbohydrates (starch and sugars) substantially modifies the physicochemical conditions of the rumen and promotes the development of amylolytic bacteria, which alters SCFA production, promoting an increase in the proportion of propionate and a reduction in acetate and butyrate. With this, there is a reduction in CH_4 production due to the decrease in the availability of H_2; that is, the reduction in H_2 production and its redirection in alternative metabolic pathways divert H_2 from the formation of CH_4 (MARTIN; MORGAVI; DOREAU, 2010; LIMA et al., 2019). Table 1 presents some results of CH_4 production of beef cattle and sheep and the technique used to measure the gas.

More efficient animals, with better consumption and residual gain (i.e., those that use food better, with less need for nutrients for each production unit), take less time to complete their production cycle and spend less energy on maintenance and in loss with CH_4 production, consequently emitting less CH_4 (COTA et al., 2014). Table 2 shows the estimates of CH_4 emission from different animal categories according to residual feed intake (RFI).

Table 1. Studies with different techniques (respirometric chambers, SF_6 and greenfeed) to estimate enteric CH_4 emission.

Technique	Animal category	Ingredient roughage diet	Emission CH_4 (g/d)	References
RC	beef cows	Lucerne chaff	216	Velazco, 2016
GF	beef cows	Lucerne chaff	209	Velazco, 2016
GF	beef steers	Lucerne chaff	215	Velazco, 2016
GF	sheep	Lucerne	27	Nguyen et al., 2016
GF	sheep	Pasture	27.7	Nguyen et al., 2018
RC	beef steers	Lucerne chaff	198	Velazco, 2016
RC	beef heifers	Barley e lucerne cubes	93	Boadi & Wittenberg, 2002
RC	sheep	brassica crops	17.2	He; Sun; You, 2021
RC	sheep	Mofumbo	9.7	Abdalla Filho et al., 2017a
RC	sheep	tifton hay	20.9	Soltan et al., 2021
RC	sheep	Tifton hay	11.5	Sakita et al., 2022
SF6	beef heifers	Barley e lucerne cubes	98	Boadi et al., 2002
SF6	beef cows	Alfafa	289.3	Stewart et al., 2019
SF6	beef heifers	Alfafa	257.9	Stewart et al., 2019
SF6	sheep	pearl millet	15.4	Amaral et al., 2016
SF6	sheep	ryegrass	10.5 a 35.9	Molano & Clark, 2008
SF6	sheep	Marcrotyloma	14.9	Lima et al., 2019
SF6	sheep	tifton hay	21.9	Campos et al., 2018
SF6	sheep	M caesalpiniaefolia	11.3	Moreira et al., 2013

Table 2. Estimate of CH_4 emission from different animal categories according to residual food intake (RFI)

Animal category	Unit of CH_4 emission estimate	RFI			References
		High	Medium	Low	
Cattle - Pregnant beef cows	g/kg live weight/d	0.26	-	0.26	Jones et al., 2011
Cattle - Lactating beef cows	g/kg live weight/d	0.46	-	0.34	Jones et al., 2011
Cattle - Finishing beef cattle	g/d	265	224	184.4	Smith et al., 2021
Cattle - heifers	g/d	297	275	260	Fitzsimons et al., 2013
Cattle - steers	g/d	190.2	-	142.3	Hegarty et al., 2007
Cattle - heifers	g/d	156.3	-	164.5	Alemu et al., 2017
Cattle - steers	g/d	265	-	194	Dini et al., 2019
Sheep – ewes	kg/d	0.027	0.023	0.021	Muro-Reys et al., 2011
Sheep - rams	kg/d	0.029	0.026	0.027	Muro-Reys et al., 2011

Ruminal parameters in sheep

The rumen environment is a complex ecosystem with a highly diverse anaerobic microbial community. This community comprises bacteria, including methanogens, fungi, protozoa, and even bacteriophage viruses. They are extremely important for the health, growth, and nutrition of ruminants (MORGAVI et al., 2010). Since the rumen can be described as a fermentation chamber where most of the nutrients in the animal diet are degraded and converted into AGCC, CO_2, ammonia (NH_3), CH_4, and microbial cells, as end products of fermentation by microorganisms, we can conclude that the study of fermentative parameters can provide valuable information about ruminant metabolism (LIMA et al., 2018).

The ruminal absorption capacity is affected by its hydrogenic potential. One way to verify whether the diet provided would be adequate for the physiological characteristics of the ruminant is the concentration of ruminal ammoniacal nitrogen (N-NH_3) (SILVEIRA et al., 2009). In the most varied situations, 40–100% of the nitrogen required by microorganisms could be derived from N-NH_3 (STERN; HOOVER, 1979). The production and measurement of ruminal N-NH_3 are good indicators of the ruminal degradability of dietary proteins (WANG et al., 2006; PIMENTEL et al., 2012; BHATTA et al., 2013).

Once in the rumen, dietary proteins are hydrolyzed to peptides and amino acids by the ruminal microbiota, which can be incorporated by the microbiota for microbial protein synthesis or deaminated, giving rise to ammonia (McDONALD et al., 2011). The ammonia from protein hydrolysis can then be used by ruminal microorganisms for microbial protein synthesis or can be absorbed into the bloodstream and transformed into urea in the liver (McDONALD et al., 2011). The presence of NH_3 in the rumen is important for the proper functioning of this ecosystem; according to the literature, the minimum ideal concentration ranges from 5 to 20 mg/dL (LENG, 1990; PIMENTEL et al., 2012). For interest in reducing methane emissions, the evaluation of N-NH_3 production in animals selected for RFI and RIG is critical, since the presence of N-NH_3 is completely related to rumen degradability.

SCFAs, produced in the rumen through the microbial fermentation of carbohydrates, are the main source of energy for ruminants. They mainly constitute of acetate, propionate, and butyrate (produced in larger proportions), followed by isobutyrate, valerate, and isovalerate, produced in smaller quantities (BERCHIELLI et al., 2006; McDONALD et al., 2011). The molar proportions are dependent on the diet consumed by the animals. The proportions of acetate, propionate, and butyrate are variable, with values ranging from 75:15:10 in diets rich in fibrous carbohydrates to 40:40:20 in diets rich in non-fibrous carbohydrates.

SCFAs are a reflection of microbial activity and absorption through the rumen wall. Generally, 60–70% of SCFAs are converted to acetic acid, 18–22% to propionic acid, 13–16% to butyric acid, and 2–4% to valeric acid (TEIXEIRA; TEIXEIRA, 2001), which can provide up to 80% of the daily energy requirement of ruminants (BERGMAN, 1990). Animals fed higher proportions of concentrates or younger forage, with greater degradability, tend to increase the proportion of propionate in relation to other SCFAs (JANSSEN, 2010). In exaggerated amounts in the rumen, SCFAs can accumulate, triggering metabolic disorders and causing negative effects on the performance and health of animals (BARKER et al., 1995). The ingestion of rapidly fermentable foods (e.g., high-concentrate diets) increases microbial activity, causing substantial fluctuation in the final products of fermentation, alteration of ruminal pH, and decrease in the proportions of butyrate and acetate, a fact that may reflect on the use of the other dietary nutrients (COSTA; PEREIRA; MELO, 2008).

Acetate is a source of hydrogen in the rumen, and propionate is a hydrogen sink, a relationship that determines CH_4 production (MORGAVI et al., 2010). The relationship between the proportions of acetate and propionate has been highlighted in studies addressing CH_4 emission in ruminant production. The synthesis of propionate by the rumen microbiota uses hydrogen ions, while that of acetate releases these ions into the medium. Acetate production leads to the highest relative production of CH_4, since $4H_2$ is formed during the fermentation of 1 mol of hexose compared to $2H_2$ for butyrate and $1H_2$ for propionate. Considering that methanogens use this H_2 to produce CH_4, lower values for the acetate:propionate ratio are associated with a lower production of CH_4 (COTTLE; NOLAN; WIEDEMANN, 2011).

For this reason, to reduce CH_4 production, the amount of hydrogen released as a result of fermentation needs to be reduced or the use of hydrogen in the production of propionic acid needs to be facilitated. While acetate and butyrate, generated from nutrient fermentation in the rumen, stimulate CH_4 production, increased propionate production is related to decreased CH_4 production (TOPRAK, 2015). That is, a change in the production of short-chain fatty acids in the rumen is expected to decrease CH_4 production, as less metabolic hydrogen is available as a methanogenesis substrate (DEMEYER, 1991). The metabolic pathways involved in hydrogen production and its utilization, as well as the methanogenic community, are important factors that must be considered when developing strategies to control CH_4 emissions by ruminants.

Protozoa were the first microorganisms to be described in the rumen environment and may represent 2% by weight of the rumen content, 40% of the total nitrogen, and 60% of the final fermentation product (KAMRA, 2005). Previous studies have indicated the importance of protozoa in digestion and in creating the balance of the rumen ecosystem, as well as in maintaining ruminant health (KAMRA, 2005). Protozoa can influence food fermentation, microbial population, the amount and proportion of rumen end products, and CH_4 production (WILLIAMS; COLEMAN, 1997; EUGENE; ARCHIMÈDE; SAUVANT, 2004). Therefore, an analysis of the protozoan population profile can present the conditions of the rumen ecosystem (DIRKSEN, 1993).

Protozoa are non-pathogenic, anaerobic, single-celled microorganisms that range in size from 20 to 200 μm (10 to 100 times larger than bacteria). The rumen content population of animals fed different types of diets varies in concentration between 104 and 106 /mL. The presence of protozoa in the rumen has its benefits as well as adverse effects. The beneficial effects include the stability of fermentation and pH, as well as the high and stable concentration of SCFA, as a consequence of starch digestion. The following are the adverse effects: high concentration of ammonia in the rumen, decrease in bacterial population, low proteolytic activity and microbial protein synthesis, methanogenesis, increased flow of N_2 to the small intestine, decreased flow of microbial protein to the small intestine, decrease in feed conversion efficiency, and decrease in weight gain (BERCHIELLI et al., 2011; KOZLOSKI, 2019).

Thus, the role of protozoa in the rumen remains controversial (NGUYEN et al., 2016). The use of defaunated animals (i.e., animals that had their protozoan populations eliminated by chemical or physical methods) allows better elucidation of the functions of protozoa in the rumen. Some studies have report that the removal of ruminal protozoa leads to a decrease in CH_4 production and the proportion of methanogenic bacteria (McALLISTER and NEWBOLD, 2008; MORGAVI et al., 2010), in addition to increasing the molar proportion of propionate and decreasing butyrate and acetate concentrations. NEWBOLD; LASSALAS; JOUNY (2015) performed a meta-analysis of several studies using defaunated ruminants and obtained the following main findings: reduced degradability of organic matter in the absence of protozoa, especially fiber; decreased concentration of N-NH_3 in the rumen due to the decrease in the breakdown of microbial and dietary protein in the absence of protozoa, which can lead to an increase in protein flow to the small intestine; decreased SCFA concentration, which indicates the importance of protozoa in the synthesis of these molecules and in food degradation; and up to 11% reduction in CH_4 production. Most methanogens live in symbiosis with ruminal protozoa, taking advantage of their outstanding ability to produce hydrogen and contributing to the methanogenesis process (NEWBOLD et al., 1995; JAYANEGARA; LEIBER; KREUZER, 2012). Due to this relationship between methanogens and protozoa, the counting of these microorganisms is frequently observed in studies related to CH_4 emission (BHATTA et al., 2009; HRISTOV et al., 2011; NGUYEN et al., 2016). As an example, Table 3 presents the main groups of rumen microorganisms evaluated in sheep under tropical conditions.

Feed efficiency measures in sheep farming

One of the methods for optimizing animal production is the classification and selection of animals according to their feed efficiency. Feed efficiency refers to the capacity with which the food ingested by animals is converted into animal products of zootechnical interest (meat, milk, and wool), which are directly related to the economic viability of the activity, since food represents a large part of production cost (GIRÁLDEZ et al., 2021). Some measures have been proposed and used to determine the feed efficiency of animals, such as RFI, proposed

Table 3. Main groups of ruminal microorganisms evaluated in sheep under tropical conditions related to CH4 emission.

Reference	Microorganisms evaluated	Function related to CH_4 emission
Abdalla Filho et al., 2017b	Rumen Fungi	Fiber colonizers, produce acetate, lactate, succinate, CO_2 and H_2.
	Methanogenic archaea	Produce methane from CO_2 and H_2.
	Ruminococcus flavefaciens	Fibrous carbohydrate fermenters (cellulose and hemicellulose), rely on ammonia and branched-chain fatty acids.
	Fibrobacter succiogenes	Fibrous carbohydrate fermenters (cellulose and hemicellulose), rely on ammonia and branched-chain fatty acids.
Campos et al., 2019	Protozoa	Ingestion of bacteria, engulfment of starch granules and lactate fermenters (avoid sudden drop in pH), reduction of microbial protein and increase of nitrogen, a producer of H_2.
	Fibrobacter succiogenes	Fibrous carbohydrate fermenters (cellulose and hemicellulose), rely on ammonia and branched-chain fatty acids.
	Ruminococcus flavefaciens	Fibrous carbohydrate fermenters (cellulose and hemicellulose), rely on ammonia and branched-chain fatty acids.
	Rumen Fungi	Fiber colonizers, produce acetate, lactate, succinate, CO_2 and H_2.
	Methanogenic archaea	Produce methane from CO_2 and H_2.
Lima et al., 2019	*Ruminococcus flavefaciens*	Fibrous carbohydrate fermenters (cellulose and hemicellulose), rely on ammonia and branched-chain fatty acids.
	Fibrobacter succiogenes	Fibrous carbohydrate fermenters (cellulose and hemicellulose) rely on ammonia and branched-chain fatty acids.
	Methanogenic archaea	Produce methane from CO_2 and H_2
Natel et al., 2019	Methanogenic archaea	They produce methane from CO_2 and H_2.
	Fibrobacter succiogenes	Fibrous carbohydrate fermenters (cellulose and hemicellulose) rely on ammonia and branched-chain fatty acids.
	Ruminococcus flavefaciens	Fibrous carbohydrate fermenters (cellulose and hemicellulose), rely on ammonia and branched-chain fatty acids.
	Selenomonas ruminantium	Lactic, use lactic acid as an energy substrate.
	Wolinella succinogenes	Proteolytic.

by Koch et al. (1963), and residual intake and gain (RIG), proposed by Berry and Crowley (2012).

The efficiency of use of food by animals varies in terms of sex, breed, physiological state, and age (PAULA, 2011). Less efficient animals may have higher catabolism rates, which increases energy expenditure with maintenance, making fewer nutrients available for production (SANTANA, 2009).

RFI is currently the most studied measure to determine the feed efficiency of animals (GRION, 2012; BERRY; PRYCE, 2014), mainly because it is not directly correlated with the rate of gain and live weight, avoiding considerable growth of the animals once they reach maturity. RFI is calculated from the linear regression of individual dry matter intake as a function of average metabolic live weight and average daily gain. It is independent of growth and maturity patterns and can be a more accurate measure of food utilization (CORVINO, 2010). The estimated dry matter consumption in RFI calculation indicates the amount of feed needed to produce one unit of product and maintain one unit of metabolic live weight (LIMA, 2016). The residue (i.e., RFI) is the difference between the observed and estimated consumption of food. Thus, the most efficient animals are those that present RFI-/lower (observed consumption is lower than estimated consumption) and the less efficient ones are those with RFI+/higher (observed consumption is greater than estimated consumption).

Another measure of feed efficiency is RIG, which selects animals that are fast growing and consume proportionately less than expected feed (BERRY; CROWLEY, 2012). Therefore, RIG identifies animals that require a shorter period in the production cycle (i.e., higher average daily gain) but also have a lower dry matter intake than expected for this growth, at the same time without differences in body weight (BERRY; CROWLEY, 2012).

Lamb, due to its high growth rate, is the category with the highest productive efficiency, resulting in higher carcass yields and better-quality meat (PIRES et al., 2000). Its production is usually associated with confinement, a practice that facilitates the exploitation of the animal's greatest earning potential in the young phase. However, finishing confined lambs can be an economically unfeasible practice due to feeding expenses, which can represent approximately 70% of the total production cost (BARROS et al., 2009).

In general, it is interesting to identify and select more genetically efficient animals, with lower consumption and greater weight gain, as these variables are important for reducing production costs, as well as the production of GHGs, such as CH_4, thus having a less negative impact on the environment (NKRUMAH et al., 2006; HEGARTY et al., 2007; SANTANA et al., 2014; LIMA, N. 2016).

To reduce the feeding costs in confinements, it is necessary, in addition to using cheaper foods in diet constitution, to maintain an efficient herd of animals. Feed efficiency is an important parameter in reducing areas for food production, allowing the selection of less polluting animals, which produce less waste and CH_4 (BASARAB et al., 2003). In addition, economic analysis in feedlot lambs showed that most efficient systems (lower RFI and higher RIG) had lower costs and higher profit margins (LIMA et al., 2017).

Ruminant feed efficiency can be a strategy to explore the reduction of enteric CH_4 emission per kg of dry matter intake or even per kg of product, and reports on beef cattle have shown positive results in this regard (HEGARTY et al., 2007; JONES et al., 2011; FITZSIMONS et al., 2013; RENAND et al., 2019; SMITH et al., 2021). Similar results were found in studies with sheep, in which low RFI Pelibuey lambs showed 17% lower CH_4 production per kilogram of metabolic weight and approximately 16% lower feed intake when compared to less efficient animals (ARCE-RECINOS et al., 2022). In addition to emitting less CH_4 per unit of dry matter intake (PAGANONI et al., 2017), low RFI lambs improve the efficiency in the use of energy and nitrogen (ELLISON et al., 2017), requiring less maintenance energy.

In some studies, with beef cattle and sheep, a positive correlation was estimated between RFI and CH_4 production; that is, animals with lower RFI (more efficient) had lower daily rates of CH_4 production. Low-RFI rams and ewes emitted less CH_4 without affecting the production parameters, with a reduction in the amount of fermented feed per kg of gain (HEGARTY et al., 2007; DINI et al., 2019; JONES et al., 2011; MURO-REYES et al., 2011; FITZSIMONS et al., 2013; ALEMU et al., 2017; SMITH et al., 2021). Regarding RIG use, the most efficient animals (higher RIG) had lower dry matter intake compared to the less efficient animals (lower RIG) and higher weight gain (BERRY; CROWLEY, 2012). Although higher daily consumption was observed in higher RIG animals compared to RFI-efficient animals, the amount of food consumed during the test period was lower in higher RIG animals compared to lower RIG animals. This was due to the characteristic of RIG, whose objective is to identify animals with accelerated growth that consume, on average, less food per day (BERRY; CROWLEY, 2012). It´s important to note that selecting for feed efficiency will lower CH_4 emissions per animal, unless more animals are kept to eat the feed not required by efficient animals (WAGHORN; HEGARTY, 2011).

Selecting sheep that are more efficient has benefits in reducing feeding costs when finishing lambs for slaughter (MUIR et al., 2020), and most studies have involved young growing sheep in feedlot environments (REDDEN, et al., 2013; PAGANONI et al., 2017). However, younger sheep are usually a small part of the flock, with mature breeding ewes consuming most feed resources on a production system and improving the feed efficiency of older ewes may also have great benefits in reducing feed costs and CH_4 emissions (MUIR et al., 2020). Despite these potential gains, there are limited studies investigating feed efficiency of mature ewes and whether this is correlated with the feed efficiency of young lambs

(ARTHUR AND HERD, 2005) and recent studies showed that RFI was not correlated between weaned lambs and adult ewes (PAGANONI et al., 2017). Evaluating RFI of maternal composite ewes at three different ages (post-weaning, hogget and adult), MUIR et al. (2020) found that RFI was phenotypically strongly correlated with dry matter intake and there were significant phenotypic correlations between dry matter intake, growth rate, RFI and CH_4 emissions, however these relationships were not consistent at post-weaning, hogget or adult ages, with insufficient evidence of RFI and CH_4 emissions correlation to determine conclusively if improvements in RIF would also reduce CH_4 emissions.

The lack of consistency among studies could relies on different factors as discussed by CANTALAPIEDRA-HIJAR et al. (2018) reviewing biological determinants of between-animal variation in feed efficiency of growing beef cattle. According to these authors, feeding and digestive-related mechanisms seems to be associated with RFI mainly because they co-vary with dry matter intake, and this should be confirmed in future studies by controlling dry matter intake in the analysis of biological determinants, combining different physiological measures in the same study, and testing the relationship in grazing conditions or with high-forage diets. Overall, it seems that efficient animals have a significantly lower energy metabolic rate regardless of the associated intake reduction, thus energy metabolism could be a true determinant of animal-to-animal variation in feed efficiency (CANTALAPIEDRA-HIJAR et al., 2018). In addition, the relevance of other significant pathways such as lipid metabolism, immunity and stress response should be confirmed combining information gathered at different molecular leves (genes, RNA, protein, and metabolites) (CANTALAPIEDRA-HIJAR et al., 2018).

Also, it is important to consider that the relations between RFI, dry matter intake and growth could differ under maintenance or restricted feeding regimes, where herbage mass becomes less available, which are more common under grazing conditions (MUIR et al., 2020). In this scenario, selecting sheep under grazing conditions may require the evaluation of different traits such as dry matter intake at different levels of herbage mass combined with measures of food seeking behavior and activity (MUIR et al., 2020).

The daily production of CH_4 is significantly affected by the amount and digestibility of the food consumed (HEGARTY, 2010). Any strategy that reduces the proportion of dietary energy spent on maintenance will reduce CH_4 emission per unit of product. A reduction in CH_4 emission can increase the animal production capacity and other measures of productive efficiency that result in shorter production cycles (COTTLE; NOLAN; WIEDEMANN, 2011). Of equal or greater importance than selecting more efficient animals is the need to select high producing animals, as this will reduce emissions per unit of product (emission intensity) (WAGHORN; HEGARTY, 2011). Research should identify high productive individuals that have low RFI to minimize the emission intensity while maintaining the production of animal-origin products.

Finally, improving feed efficiency is related to increasing the feed utilization rate, maintaining an equal or superior production performance using fewer inputs, excreting less feces and emitting less CH_4 (BASARAB et al., 2003; LANNA: ALMEIDA, 2004). The extent to which the selection of more efficient animals can lower CH_4 emissions will be determined by the heritability of efficiency, the dispersal of efficient animals over all populations, and their resilience or robustness in a production system. RFI has the advantage of lowering GHG emissions because it may be used regardless of confined, intensive, or extensive grazing systems, especially because efficient animals are likely to boost farm profitability (WAGHORN; HEGARTY, 2011). Efficient animals already exist in all herds and flocks, and research must be conducted to identify and remove inefficient individuals, while retaining and ensuring efficient ones are fit to purpose (WAGHORN; HEGARTY, 2011).

CONCLUSION

Animal selection according to the feed efficiency measures can be a sustainable technique in animal production. In the case of sheep, the selection of more efficient animals, in addition to less food consumption, can produce less enteric CH_4. With this, sheep farming can be developed in a more sustainable and profitable manner, producing quality food with reduced impacts on the environment.

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